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Traffic flow consideration in design of freight distribution system

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ABSTRACT

This study is part of a series of research projects on a distribution system we developed to deal with cases in a state-owned company. It concerns the design of the Public Service Obligation State-owned Company (PSO-SOC) distribution system. The intrinsic features of PSO-SOC are distributing strategic commodities and having subsidies within the cost function. Hence their distribution flow has to be secured under consideration of moving the commodities within road networks that have traffic flow dependency. This paper focuses on the solution of the proposed model which represents traffic flow dependency within a freight distribution network.

The mathematical formulation takes the form of a Minimum Cost Multicommodity Flow (MCMF) problem. Traffic flow dependency is incorporated into the model by introducing a coefficient of speed, which is derived from the traffic assignment of ordinary traffic associated with the transportation of the type of freight under consideration The solution of the proposed model is formulated by Network Representation (NR), in which all of the components of the mathematical model are represented in the form of dummy links and nodes added to the original (physical) network. It is to be noted then, that the traffic flow on each road or link is represented by a link performance function (LPF), depicting traffic flow dependent travel time and consequent cost. The MCMF problem of NR is further solved by a Primal–Dual Algorithm.

Finally, an illustrative example is exercised to show how the proposed step-wise solution works.

1. Introduction

Research on designing freight distribution systems has been done for many years. Most deal with a private company whose primary concern is merely profit maximization. In Indonesia, there exists a subsidized service by State-Owned Company (SOC) called Public Service Obligation (PSO)-SOC. PSO-SOC has the obligation to serve the entire demand on public commodities or services. Its working orientation is not for profit, but for security of supply. The PSO-SOC is still permitted to conduct its own programs beyond its main task, but it is undertaken within government control and limitation. The PSO-SOC also bears strategic commodities in distribution, so availability of commodities at the right time and place is important. Most of those commodities are being transported through surface land transport with mixed-traffic, so travel time and cost are very much dependent on the flow of vehicles within the road network.

The identification of the distribution system of one of Indonesia's PSO-SOCs, which deals with the production and distribution of public commodities, provides insight to some important issues as follows [1]:

1. The company under consideration is a group of companies that consists of 1 (one) holding company and 5 (five) affiliated companies. Each of the companies (included the holding company itself) carries out the operation of its own plant and its distribution process independently. Those companies are managed separately and there is no regulation that integrates those companies in their logistical process.
2. Unit production costs are not uniform among the plants. This is due to the different prices of raw material and the variability in the operation performance of the production processes.
3. Product differentiation exists. This implies that products are not differentiated merely by type (material) of product, but also by the type of user. There are two types of user, public (subsidized) and commercial. Both of them are different in terms of selling price and demand satisfaction. Subsidized prices are determined by the government, while the commercial ones are set by the company. Naturally, the commercial prices are higher than the subsidized ones. Moreover, subsidized demands have the privilege of being fully satisfied regardless of the amount of profit that the company may receive from them.

Previous research on freight distribution systems was concerned mostly with private companies [2–4]. Most of the research on the distribution of public needs is related to public services (such as schools, police stations, hospitals, etc.) rather than public goods. Savas [5] focused his research on the equity in providing public services,

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while Ross [6] proposed a model with multicriteria to select sites for public facilities. Regarding the variables included, most of the research focused on transportation costs, while some dealt with various other variables, such as production cost, fixed cost of facility, inventory holding cost, and anything relevant to the special problem they faced [2,7–9].

Moreover, most of the research on freight distribution systems hardly consider the effect of ordinary traffic movement on the system. The FHWA reports [10] that the private and public sectors of the freight industry bear an operational cost of congestion which is as much as \$25–200 an hour, depending on product type and other factors. The report also estimates that unexpected delays can increase the cost of transporting goods by 50–250%. Jones [11] explains that for the freight industry and trucking companies, congestion on the transportation network diminishes productivity and increases the overall cost of transportation services significantly. Other effects of traffic delays are a higher cost for fleet operations, decreased fleet and vehicle utilization, decreased fuel efficiency, increased emissions due to idling, and decreased hours of “productive” service for drivers.

These intrinsic characteristics clarify the need to enhance the earlier distribution models for the purpose of taking into account the special role of a state-owned company and considering the movement of the commodities within road networks that have traffic flow dependency.

2. Model formulation

In order to take into account the characteristics of the PSO-SOC as stated in Section 1, we propose that the distribution system of the affiliated companies should be integrated into one system which is coordinated by the holding company. Furthermore, we propose a distribution model which deals with production cost, transportation cost, warehouse cost, as well as revenue as its variables [1]. These variables are considered for the following reasons. When the total plant capacity is more than the total demand, the holding company has to designate production allocation to each plant, and in such a situation, one or more plants must be under capacity (not operated in full capacity). When the holding company only considers the distribution cost, it may lose efficiency on logistics as a whole, particularly if the cost of production is not in accordance with the efficiency at the distribution cost level.

In the case of over demand, all of the plants must be fully operated. In such case, the holding company must decide which commercial demands should be satisfied in order to attain the maximum profit of the company. Since the selling price of commercial products varies significantly, the selling price becomes a very important variable to be included in this optimization.

Regarding ordinary traffic considerations, we propose that a coefficient of speed be included in the model. The coefficients of speed are derived from ordinary traffic assignments which produce user-equilibrium link travel time and the associated speeds. It is actually quite valuable to consider the effect of ordinary traffic on the movement of freight vehicles, since it will lead to more informed and efficient decisions for freight allocation. Indeed, the decision to assign some amount of products to a set of plants and distribute them to a set of end consumers through certain paths is crucial to maintaining low transportation costs since these costs are highly affected by traffic performance on any given path.

The PSO-SOC under consideration takes into account only transportation costs and it does not consider the ordinary traffic flow effect in its product allocation process. Besides, the process is carried out by each plant independently (each plant is operated exclusively by one affiliated company) and there is no integration with the holding company.

In order to be more precise in making decisions on product allocation, we propose a model which deals with the cost of producing, transporting, and handling the commodities [1], as well as revenue, and includes the effect of ordinary traffic on the product allocation decision. Product allocation is also proposed to be optimized by integrating logistic subsystems of all plants.

In order to cope with the problem of a distribution system characterized mainly by product/demand differentiation, integrated systems, as well as traffic flow dependency, we propose a mathematical model which is applicable to the following distribution network, as depicted in Fig. 1. It consists of a set of plants, consolidation centers and retailers.

The proposed mathematical model is as follows:

$$
\begin{aligned}
\min Z(\alpha_{p(m)c},\beta_{crm},\gamma_{p(m)r}) = {} & \sum_{p\in P}\sum_{c\in C}\sum_{m\in M}\mu_{pc}\cdot d_{pc}\cdot u_{pcm}\cdot\alpha_{p(m)c} \\
& + \sum_{c\in C}\sum_{r\in R}\sum_{m\in M}\mu_{cr}\cdot d_{cr}\cdot v_{crm}\cdot\beta_{crm} \\
& + \sum_{p\in P}\sum_{r\in R}\sum_{m\in M}\mu_{pr}\cdot d_{pr}\cdot z_{prm}\cdot\gamma_{p(m)r} \\
& + \sum_{p\in P}\sum_{c\in C}\sum_{m\in M}w_{cm}\cdot\alpha_{p(m)c}\sum_{p\in P}\sum_{m\in M} \\
& \times\left(\sum_{c\in C}\alpha_{p(m)c}+\sum_{r\in R}\gamma_{p(m)r}\right)\cdot\eta_{p(m)} \\
& -\sum_{r\in R}\sum_{m\in M}\left(\sum_{c\in C}\beta_{crm}+\sum_{p\in P}\gamma_{p(m)r}\right)\cdot\rho_{rm}
\end{aligned}
\tag{1}
$$

$$
\mu_{ij} = 1-\frac{v_{UEij}-v_D}{v_D} \tag{2}
$$

subject to

$$
\sum_{p\in P}\alpha_{p(m)c} = \sum_{r\in R}\beta_{crm}, \qquad \forall c\in C, \forall m\in M \tag{3}
$$

$$
\sum_{c\in C}\beta_{crm}+\sum_{p\in P}\gamma_{p(m)r} = \lambda_{rm}, \qquad \forall r\in R, \forall m\in M_s \tag{4}
$$

$$
\sum_{c\in C}\beta_{crm}+\sum_{p\in P}\gamma_{p(m)r}\le\lambda_{rm}, \qquad \forall r\in R, \forall m\in M_c \tag{5}
$$

$$
\sum_{c\in C}\sum_{m\in M}\alpha_{p(m)c}+\sum_{r\in R}\sum_{m\in M}\gamma_{p(m)r}\le Cp_{p(m)} \qquad \forall p\in P, \forall m\in M \tag{6}
$$

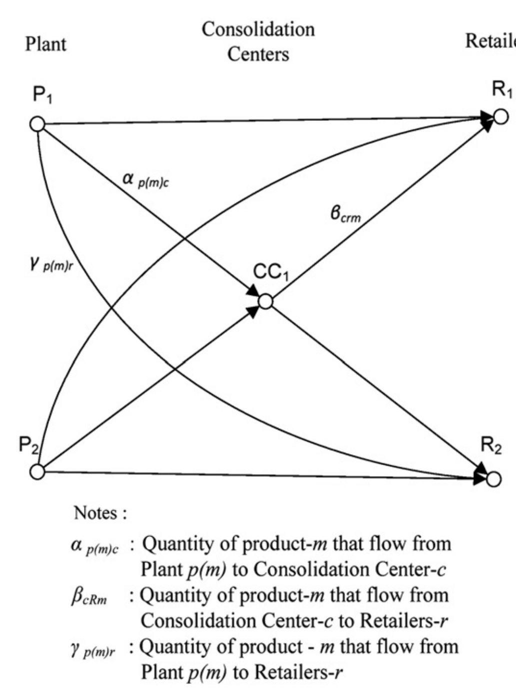

Fig. 1. An example of a physical distribution network.

$$\alpha_{p(m)c} \geq 0, \qquad \forall p \in P, \forall c \in C, \forall m \in M \tag{7}$$

$$\beta_{crm} \geq 0, \qquad \forall c \in C, \forall r \in R, \forall m \in M \tag{8}$$

$$\gamma_{p(m)r} \geq 0, \qquad \forall p \in P, \forall r \in R, \forall m \in M \tag{9}$$

Subscripts

p: indicate the plants
c: indicate the consolidation centers
r: indicate the retailers
m: indicate the products
$p(m)$: indicate the plant $p \in P$ that produces product-m

Sets

P: set of plants
C: set of consolidation centers
R: set of retailers
M: set of products
$M^s \in M$: set of subsidy (public) products
$M^c \in M$: set of commercial products

Decision variables:

$\alpha_{p(m)c}$ is quantity of product-m that flow from plant $p(m)$ to consolidation center-c
β_{crm} is quantity of product-m that flow from consolidation center-c to retailer-r
$\gamma_{p(m)r}$ is quantity of product-m that flow from plant $p(m)$ to retailer-r

Input parameters

u_{pcm}: per-mile cost to ship a unit of product-m from plant-p to consolidation center-c
v_{crm}: per-mile cost to ship a unit of product-m from consolidation center-c to retailer-r
z_{prm}: per-mile cost to ship a unit of product-m from plant $p(m)$ to retailer-r
d_{ij}: length of distance of link i–j
μ_{ij}: coefficient of speed of link i–j
$v_{UE_{ij}}$: user-equilibrium speed of link i–j
w_{cm}: unit warehouse cost to handle product-m in consolidation center-c
$\eta_{p(m)}$: unit cost for producing product-m in plant-p
ρ_{rm}: selling price of product-m at retailer-r
$Cp_{p(m)}$: capacity of plant-p to produce product-m
λ_{rm}: demand of product-m in retailer-r
$v_{D_{ij}}$: design speed of link i–j

Eq. (1) denotes the objective function of the proposed model. It actually maximizes the profit, in which profit is represented by revenue minus cost. Similarly, this objective function can be replaced by a minimization of cost function, which is represented by cost minus revenue.

The first three terms of Eq. (1) represent transportation cost, in which each term includes a coefficient of speed. Each coefficient of speed is exclusive for a certain link. It is derived from the user-equilibrium speed of an ordinary traffic assignment and design speed, as formulated in Eq. (2). The use of coefficients in Eq. (1) is meant to indirectly make corrections to the design unit cost through a correction of the design speed due to the dynamics of traffic conditions in real life situations. Since traffic conditions are very dynamic in nature, the time windows considered should be carefully selected. Moreover, this coefficient indicates that the smaller the speed (the more congested the road) the longer the "distance" that the freight vehicle should travel. The fourth term of Eq. (1) is related to warehouse cost. The fifth term represents production cost and the last term concerns revenue. Obviously, due to the opposite characteristics of cost and revenue, we must put a minus sign before revenue. Eq. (3) denotes that the total inflow minus the total outflow in consolidation centers is set at zero since those nodes are intermediate nodes.

Eqs. (4) and (5) are related to demand satisfaction for subsidized products and commercial ones, respectively. Subsidized products must be entirely fulfilled, while the commercial ones could be satisfied later, in the case of excess plant capacity. Eq. (6) implies that the total amount of production of any product by each plant should not be more than its capacity. Eqs. (7)–(9) ensure non negativity of flow constraints.

3. Model solution

Since the MCMF problem is highly related to the network structure, we utilize Network Representation (NR) to represent and solve the proposed mathematical model. Network Representation (NR) is a technique used to solve a problem by representing a mathematical model as a network flow-based formulation [12]. It is characterized by the use of diagrams that have emerged, by progressive expansion, from those used traditionally in network flow and graph theory. Network Representation is developed by adding some dummy links and nodes into the original (physical) network, in which the function of those dummy links is designated to represent production cost, transportation cost, and warehouse cost, as well as revenue.

One particular issue regarding our MCMF problem is the involvement of multi-commodities in the distribution system. This issue is solved by introducing a Sub-Network Representation devoted to a certain product. We name such sub-NRs as Product Sub-Network Representation (P-SNR). Each P-SNR is exclusively devoted to a certain product, and consists of nodes and links used by that certain product, although it is possible that some of the links of a P-SNR are used for common products.

In order to cope with the situation of an imbalance between total supply and total demand, we developed an Excess Supply/Demand Sub-Network Representation. Its function is to balance the total supply and total demand endogenously in the optimization process, by decreasing the demand or supply so that both of them finally are in balance.

An example of a general NR is shown in Fig. 2. It consists of 2 plants, 1 consolidation center and 2 retailers, and it deals with 2 types of products and 2 types of demand (subsidized and commercial demand). The P-SNRs of such an NR are shown in Fig. 3a and b.

Links between node P_{i-m} and P_i are designed as production cost links. Each link represents the cost to produce product-m in plant-i. Each of those links is also characterized as a product-exclusive link; that is each link is devoted to a certain product. Hence, in Fig. 3a, which shows the P-SNR of product-1, there are only nodes and links that relate to product-1 (link P_{11}–P_1, P_{21}–P_2).

Links between P_i–CC_i, P_i–R_i and CC_i'–R_i are designed as transportation cost links, and they represent the transportation cost between two distribution facilities. It is assumed that the unit cost to transport any type of product in a certain link is similar. Coefficients of speed are employed in each transportation cost link. The link between CC_i–CC_i' represents the cost of using warehouse-i. Every one unit of flow that comes to the consolidation center is charged by one unit of warehouse cost. Links between node R_i and R_{i-m} are designed as revenue links. Those links represent revenue from selling product-m to retailer-r. Each revenue link is also designed as a product-exclusive link. Unit cost associated to revenue link is denoted by selling price. All of the

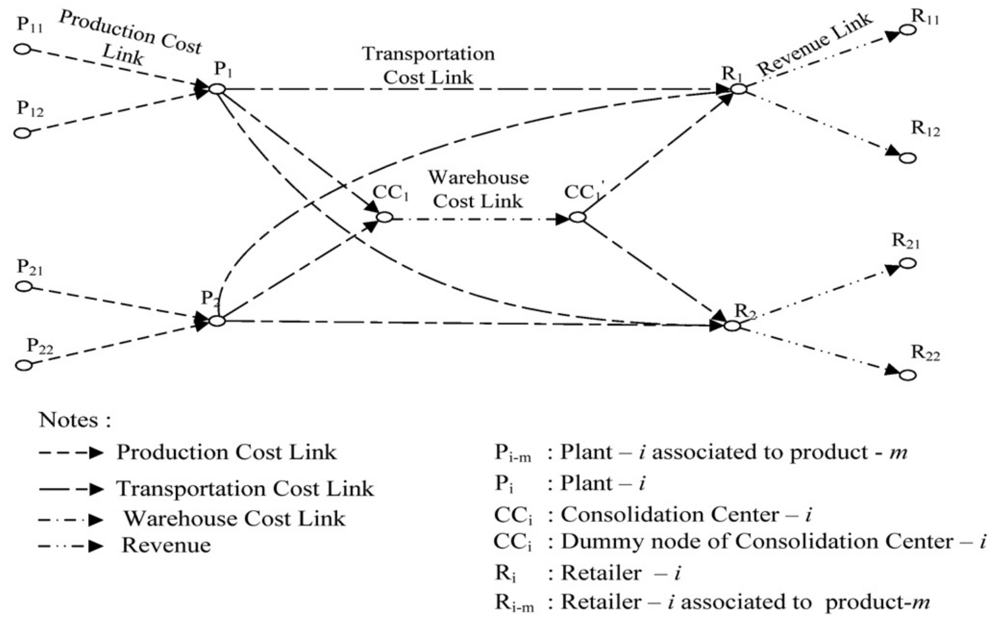

Fig. 2. An example of a Network Representation.

links of the NR are designed as un-capacitated links; hence there will be as many flows as possible passing through the links.

In a real situation, the total supply is not always in balance with the total demand. In some cases, the total supply is higher than the total demand. In such excess supply cases, the company should be selective in making product assignments to each plant. In excess demand cases, in which the total demand is higher than the total supply, the company should be selective in demand satisfaction. In the case of the PSO-SOC, subsidized demand should have priority to be fulfilled, no matter what the profit that the company could attain from it. Regarding both cases, we developed an Excess Supply/Demand Sub-Network Representation in order to accommodate both situations and to make the supply and demand be always in balance during the optimization process. Fig. 3a depicts the NR in the excess demand case, in which we added a Dummy Plant to act as a supply for the excess demand. Fig. 3b depicts the excess supply case, in which we added a Dummy Retailer to act as a receiver for some excess products from nodes of plants.

In order to give priority to the subsidized demand, we designate an extremely high unit cost to the links of the excess Demand Sub-Network that relates to nodes of subsidized (public) demand. This means that

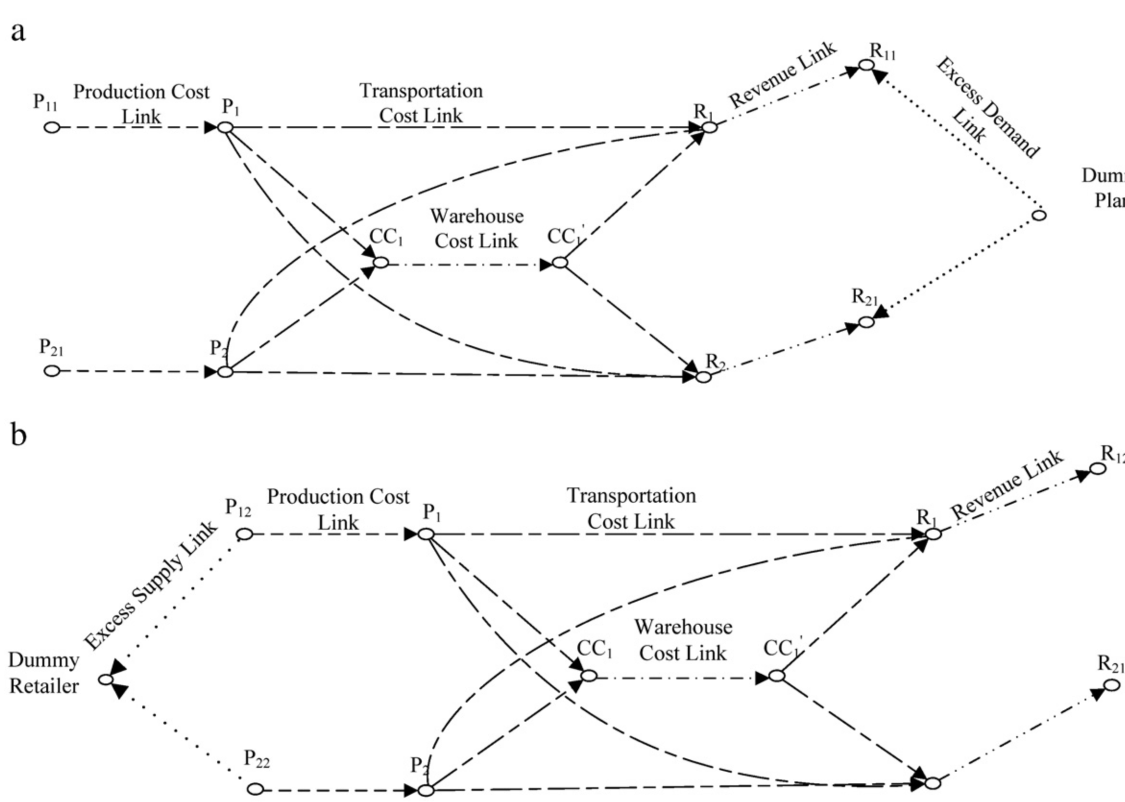

Fig. 3. a. Product Sub-Network Representation of product-1 (in Excess Demand case). b. Product Sub-Network Representation of product-2 (in Excess Supply case).

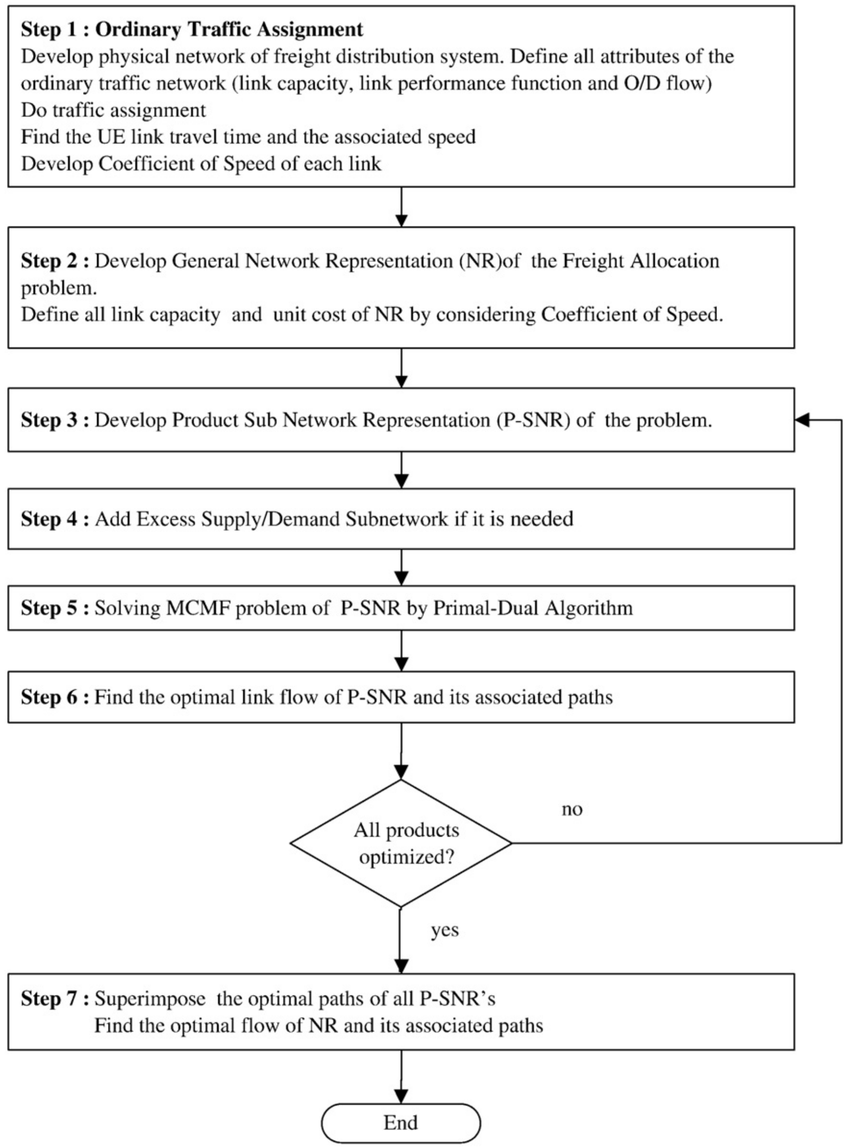

Fig. 4. Step-wise of model solution.

such a high "unsatisfied-demand cost" will cause the model to avoid unfulfillment of public demand.

The nodes of the NR are valued as their flow requirement. Node P_{i-m} is valued by the capacity of plant-*i* on producing product-*m*, meanwhile node R_{i-m} is valued by the demand on product-*m* in retailer-*i*. The flow requirements of the intermediate nodes are set as zero.

Having the NR formulation, the problem now is how to determine the optimal assignment of the products to attain the "minimum cost". The minimum cost flow problem is solved by a Primal–Dual Algorithm [13]. We propose a step-wise solution of the MCMF problem as depicted in Fig. 4. It can be explained as follows:

Step 1: The process is initialized by doing traffic assignments to the ordinary traffic of the physical network of the freight distribution system. Provide the attributes of the ordinary traffic network, including link capacity, link performance function and O/D flow. Set the time window and do traffic assignments to find the user-equilibrium link travel time and the associated speed. Provide the Coefficient of Speed of each link using Eq. (2).

Step 2: Develop the General Network Representation (NR) of the freight allocation problem. Define the link capacity and the flow requirement as well as the unit cost of the NR by considering the Coefficient of Speed of step 1.

Step 3: Develop product sub-NR (P-SNR) of all types of products.

Step 4: Add an Excess Supply/Demand Sub-Network to the P-SNR of step 3; if it is needed, include setting of its link capacity and unit cost.

Step 5: Solve the MCF problem of the P-SNR by using a Primal–Dual Algorithm.

Step 6: Find the optimal flow and its associated paths through the P-SNR. Steps 3–6 are repeated until all products are optimized.

Table 1
Plant capacity.

Plant	Plant capacity (units)	
	Product-1	Product-2
1	140	100
2	210	660
Total	350	760

Table 2
Demand on certain product.

Retailer	Demand on product (units)			
	1^S	1^C	2^S	2^C
1	50	20	10	30
2	30	10	20	40
Total	110		100	

Notes: s: subsidy; c: commercial.

Since one P-SNR is independent to another P-SNR, steps 3–6 are actually able to be carried out in a simultaneous way.

Step 7: When all the P-SNRs have been optimized, superimpose the optimal paths of all P-SNRs and find the total optimal flows on each link of the NR. Superimposing is allowable since it is assumed that unit cost to transport and handle any type of product in a certain link is similar, and each link of production cost, as well as revenue links, is characterized by a product-exclusive link.

4. Illustrative example

In an attempt to apply the step-wise proposed in Section 4, the ensuing contrived example is discussed. The distribution network of the example consists of 2 plants, 1 consolidation center and 2 retailers. It deals with 2 kinds of products and 2 kinds of demand (subsidy and commercial). Plant capacity and demand on each product are shown in Tables 1 and 2 respectively.

We exercised this example with 3 cases. In the first case, it is assumed that coefficients of speed of all links are one. In the second and third cases, it is assumed that step 1 of the step-wise model is already done and 2 sets of link coefficients of speed were found. The first set is derived from a traffic assignment which is based on user-equilibrium with an average speed of 58.63 units (case 2) and the second one is based on user-equilibrium with an average speed of 61.2 units (case 3).

Table 3
The assignment of the products.

Retailer	Product	Supplied by plant		
		Case 1	Case 2	Case 3
		Objective value = −2670	Objective value = −2538	Objective value = −2896
1	1^S	1	2	1
2	1^S	1	1	1
2	1^C	1	1	1
1	1^C	1	2	1
1	2^S	2	2	1
2	2^S	1	1	2
2	2^C	1	1	2
1	2^C	2	2	1
Average speed		60 (Design speed)	58.63	61.2

Notes:
s: subsidy; c: commercial.

The optimal flow of the three traffic assignments is shown in Fig. 5 and the associated product assignment is displayed in Table 3. The values of the objective function, as well as the patterns of product assignment of all cases, are changed as the coefficient of speed changes. It can be concluded that the coefficients of speed are sensitive to the product assignment, as well as the value of the objective function. Moreover, it can be said that ordinary traffic flow is a necessary factor to be considered in designing a freight distribution system model in order to make it more realistic.

5. Conclusion

We propose an allocation model which considers traffic flow dependence and the characteristics of the PSO-SOC. Traffic flow, that may increase travel cost through LPF and hence distribution cost, is accounted for within the traffic assignment. By doing so, the flow of commodities within mixed-traffic will implicitly represent cost performance due to the nature of traffic flow situations. The proposed model

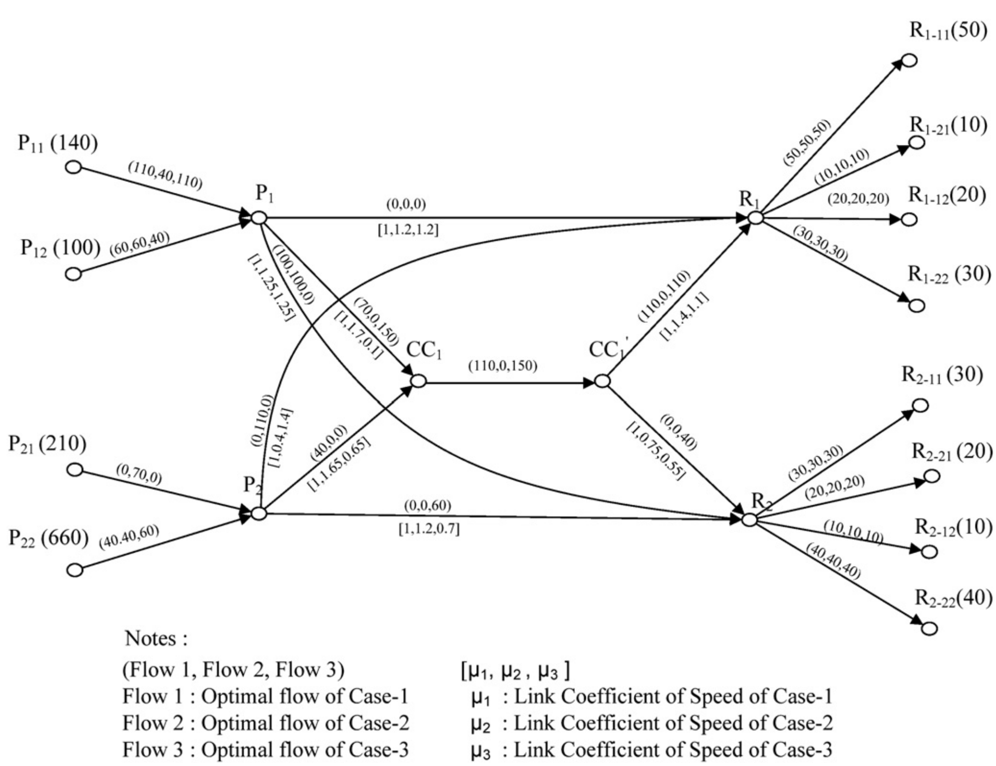

Fig. 5. The optimal flows of 3 (three) distribution assignments.

takes the form of a Minimum Cost Multicommodity Flow problem and the solution is formulated by Network Representation.

Calibration of the model may be required when dealing with real cases in determining the coefficients of speed. The speed coefficient given in the example is a simple one to represent the relation between traffic flow patterns and the pattern of distribution. A more realistic one, which is close to a real condition representation, may be made with an empirical process through model calibration. The three cases given in exercising the model merely denote the different distribution patterns due to different traffic patterns. Those three cases use different values for the objective function, but they all are based on flow equilibrium conditions that can be made to cope with dynamic traffic flows in practical cases.

This research work is essentially intended to give a contribution to the research field of freight distribution within mixed-traffic, as well as to the distribution system of a PSO-SOC within the proposed assumptions.

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